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Astrometric observations of Nereid in 2006-2007 ⋆⋆

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ABSTRACT

In this paper, we present 112 new CCD astrometric positions of Nereid, the second and faint satellite of Neptune ($m_v \simeq 19$). We observed this small satellite in the 2006-2007 period with the 1m and the 2.16m telescopes of Xinglong Station near Beijing, both equipped with large CCD detectors of 1340×1300 and 2048×2048 pixels, respectively. The high-density and highly accurate star catalogue UCAC2 (Zacharias, 2004) was used in the reduction so that a classical astrometric calibration method was applied. We have shown that our observations of Nereid appear to be of equal or higher precision ($\sigma \simeq 0.2$") than most of the recent CCD ones.

Key words: planets and satellites - satellites of Neptune - astrometry

1 INTRODUCTION

Since Kuiper discovered Nereid in 1949, this satellite has been poorly observed due to its extremely difficult observing conditions: an **extreme faintness,** with a visual magnitude m_v of about 19.5, and an irregular orbit. However, after the Voyager 2 spacecraft successfully accomplished a passage through the Neptune system in 1989 August 25, Nereid has attracted some more interest and **attention of** the scientific community. In order to facilitate the future space exploration, more knowledge of the positions of this small satellite **has become a pressing** requirement.

Nereid is one of the most **distinctive** satellites that we know in the solar system. The distance from Nereid to its Primary much varies, from about 1,4 to 9,6 million km, due to its very large excentricity ($e \simeq 0.75$). Furthermore, its orbit has a rather long period of about 360 days and a large inclination with respect to Neptune's equator ($i \simeq 27$ degree). These distinctive features of Nereid's orbit have made this satellite difficult to observe, hindering further research on it. Based on these peculiarities, the study of Nereid's orbit is one of the inspiring ways to acquire better knowledge of the solar system. Towards this end, more efforts have been made for obtaining new highly accurate observations of Nereid. However, before our observations made in 2006-2007, only less than 600 observed positions were obtained in the past. In 1989, the Voyager 2 spacecraft approach near the Neptunian system provided 83 unpublished positions determined by Jacobson et al.(1991). All the other observations of Nereid are ground-based observations. Before the Voyager 2 approach, 70 astrophotographic observations were accomplished. The first three of them were made by Kuiper (1949). Then, van Biesbroeck observed Nereid in a continuing program of solar system objects at Mac Donald Observatory from 1950 to 1969 (van Biesbroek, 1951, 1957; van Biesbroek et al., 1976). All the data so obtained was used by Rose (1974) to present a new orbit of this satellite. Then, 17 new observed positions were obtained by Veillet (1982) and by Veillet & Bois (1988) who also derived a new orbit of Nereid from the theory developped by Mignard (1975, 1981). Landgraf (1988) observed 5 new positions and Schaefer & Schaefer (1988) **made** 4 new ones. The last astrophotographic observations were made by Veiga et al. (1996), with 8 new positions. Later on, Veiga et al. (1999) provided 230 new positions which were the first CCD observations of Nereid. More recently, new CCD observations of Nereid have been collected by the Minor Planet Center. The IMCCE presents

⋆ The data are available in electronic form as Supplementary Material to the online version of the paper on Blackwell Synergy, at the CDS via Anonymous FTP to cdsarc.u-stasbg.fr or via http://cdsweb.u-strasbg.fr/Abstract.html.
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Table 1. Specifications of the two telescopes and CCD chips used for the observations of Nereid

	Telescope A	Telescope B
Diameter of primary mirror	$216cm$	$100cm$
Focal length	10000mm	7800mm
Size of CCD array	2080x2048	1340x1300
Size of pixel	$15\mu m$	$20\mu m$
Angular extent per pixel	$0.31''$	$0.53''$
Field of view	$10.7' \times 10.5'$	$11.7' \times 11.4'$

175 of these recent CCD observed positions, as available on their web site.

We initiated in 2006 a new attempt to perform CCD astrometric observations of Nereid. This Nereid campaign of observation is part of a wider campaign of CCD observing faint planetary satellites, that we began in 1994 (Qiao et al., 1999; 2006; 2007). Since 2006, for observing Nereid, we have been using the two reflectors of National Observatory at Beijing. Thus, we used the 1m reflector, and especially the 2.16m diameter reflector for its stronger power to detect faint objects than the 1.56m reflector of the Sheshan Station, near Shanghai, that we used in our previous campaigns of observations. As a result, we present in this paper the 112 accurate CCD astrometric positions of Nereid, that we obtained during both of 2006 and 2007 Neptune oppositions. Thus, an analysis of these observations is made to evaluate their level of accuracy and to compare it to that of observations made by previous authors.

2 OBSERVATIONS, MEASUREMENT AND REDUCTION

2.1 Our observations

All our astrometric observations of Nereid were performed at Xinglong Station (IAU code number 327), near Beijing, which is an observing station of National Observatory, Chinese Academy of Sciences. Xinglong Station is located at E117.577 degree, N40.396 degree and H940.0 meters. We successively used the 1m and the 2.16m telescopes, both equipped with large CCD chips of 1340×1300 and 2080×2048 pixels, respectively. Accordingly to the focal length of each telescope (7.8m and 10m) and to the size of the pixels of each CCD chip, the available field was about $11' \times 11'$for both of these instruments. The complete specifications of the two instruments with their respective CCD chips are listed in Table 1. A total of 112 astrometric positions were so obtained in four successive observing periods, spanning from 2006 to 2007. For the first one, in August 2006, we obtained 15 positions with the 2.16m telescope (set 216a). In the second period of August 2007, we used the 1m telescope to obtain 17 new positions (set 100a). The third period was just a few days after in the same month, and we observed 34 new positions with the 2.16m telescope (set 216b). During the fourth and last period of observation of this campaign, in September 2007, we used the 1m telescope for obtaining 46 new positions of Nereid (set 100b).

The flat-field images were taken at dusk and dawn. The bias is taken at the beginning and at the end of the observation. The dark field images were taken at the end. No filter was used during our observations of Nereid. The exposure time was about $2 - 10$ minutes, depending on the weather conditions, elevation above horizon, and the setting of the different telescopes. In Fig. 1, two typical CCD images of Nereid taken at different times are presented. **These are raw images, without any dark or flat field correction, showing the original map of the data.** In the frames, Nereid is indicated by an arrowhead, and its motion relative to stars appears quite visible.

2.2 Measurement and data reduction

In previous astrometric reductions of satellite observations, calibrating the CCD frame was very difficult, in connection with the lack of reference stars, due to the limitation of the small size of CCD chips and to the low density of previous star catalogues. Consequently, authors had either to use secondary star catalogues or theoretical differential positions of satellites with respect to other satellites or to the Primary, as did Shen et al. (2001) for the Saturnian satellites. In the peculiar case of Nereid, the high difference of its magnitude with Neptune's could affect the determination of its relative positions. With the development of technology, large CCD chips began to be available to observe astrometric positions of planetary satellites, as we did in our latest campaigns. In addition, with the recent high density astrometric accurate catalogue UCAC2 (Zacharias et al., 2004) providing more than 48 million reference stars, enough number of reference stars can be found in the same CCD frame to perform a classical astrometric reduction. Consequently, in this work, we have been able to directly obtain the absolute positions of the satellite Nereid, and so, its relative positions with respect to Neptune did not need to be measured.

In our four observing periods, the average value of Full Width at Half-Maximum (FWHM) was calculated for determining the value of seeing. The range of seeing in Xinglong Station appears to be about $1.5 - 3.5$ arcsec, typically 2.5 arcsec. We use the powerful ASTROMETRICA software to determine the positions of the star center and satellite images. Astrometric Data Reduction command applies a two-dimensional Gaussian fitting to every image and a term of second-degree polynomial to represent the background level. The centering error of Nereid is rather significant, with about 0.08 arcsec, because of the extreme faintness of this small satellite. Accordingly, we had to take rather long exposures to obtain the images of Nereid and so, the images of stars brighter than 16 magnitude could be saturated **in the same CCD images. Such CCD frames with saturated images were eliminated. For example, during the 216a set, we obtained more than 50 CCD frames. Many of them were taken with a rather long time exposure of 900s, due to variable bad weather conditions. Finally, we only kept the 15 CCD frames without any saturated images.**

Since the high-dense star catalogue UCAC2 (Zacharias et al., 2004) was used for our astrometric calibration of the CCD frames, there are about 8 to 16 UCAC2 reference stars available in each CCD images. This number is quite sufficient to let us use the six-constant model of reduction. So, we performed an accurate classical astrometric calibration method, without using any secondary star catalogue or any

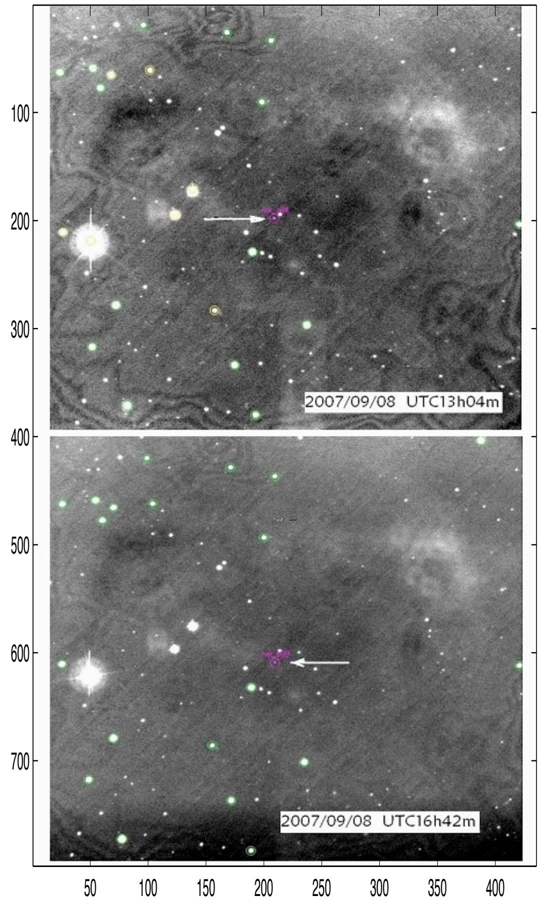

Figure 1. Two typical CCD images of Nereid are presented. In the frames, Nereid is indicated by an arrowhead and its motion relative to stars is very clear.

Table 2. An extract of the list of the observed positions of Nereid

year	Month	Day(UTC)	α	δ
2007	08	08.692362	21 33 00.238	-14 49 27.99
2007	08	08.702084	21 33 00.184	-14 49 28.59
2007	08	08.711807	21 33 00.121	-14 49 28.79
2007	08	09.564583	21 32 54.742	-14 49 55.50
2007	08	09.569444	21 32 54.691	-14 49 55.37
2007	08	09.574306	21 32 54.670	-14 49 55.73

other indirect method which could have affected the accuracy of the derived observed positions of Nereid.

In Table 2, as an example, we list some of our observed positions of Nereid. **To most observers with a consistent data format these data are topocentric and given in the ICRF J2000 system.** The complete data can be obtained on the web site of the CDS at the following address: http://cdsweb.u-strasbg.fr/Abstract.html, or via Anonymous FTP to cdsarc.u-stasbg.fr.

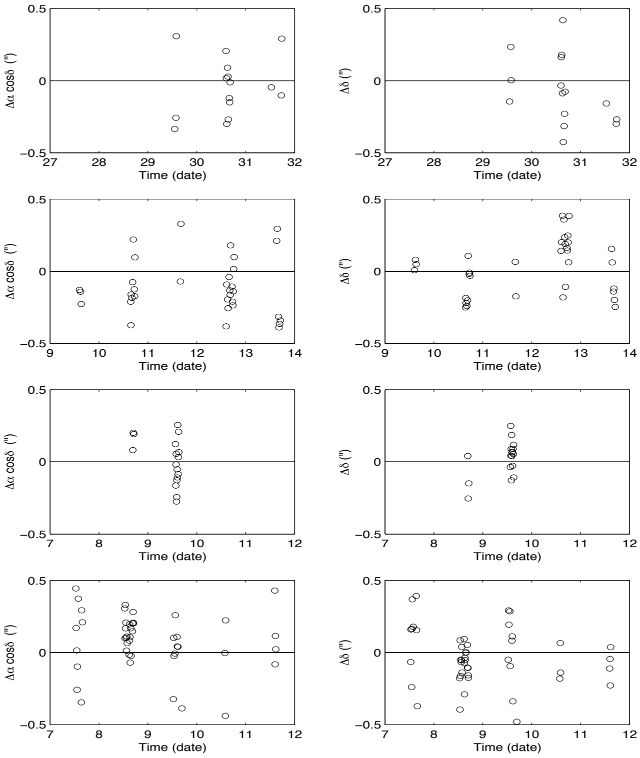

Figure 2. O-C of Nereid in 2006-2007 relative to the four sets of observations 216a, 216b, 100a and 100b from above to below

Table 3. Values of mean residuals μ and standard deviations to the mean σ relative to the four successive sets of observations

set		N	σ(")	μ(")
216a (2006/08)	$\Delta\alpha\cos\delta$	15	0.215	0.001
	$\Delta\delta$	15	0.235	-0.036
216b (2007/08)	$\Delta\alpha\cos\delta$	34	0.194	-0.112
	$\Delta\delta$	34	0.191	0.026
100a (2007/08)	$\Delta\alpha\cos\delta$	17	0.161	0.009
	$\Delta\delta$	17	0.126	0.020
100b (2007/09)	$\Delta\alpha\cos\delta$	46	0.200	0.082
	$\Delta\delta$	46	0.193	-0.035

3 ANALYSIS OF OBSERVATIONS

3.1 Comparison with theoretical positions

In the 70's of last century, Mignard (1975, 1981) set up a theory of the motion of Nereid including solar perturbations. Since 90's, Jacobson (1990, 1991) successively proposed several further improvements of the theory of Nereid. The equations of motion and variation equations used in the Jacobson's dynamical model, quite suitable for the construction of outer planet satellite ephemerides, are identical to that previously given by Peters (1981). In a forthcoming paper, we plan to develop a new numerical theory of Nereid after fitting the **additional** materials including our own observations.

In Jacobson's model, the perturbation forces of Nereid include the gravitational effects of the oblate primary, the perturbations of the barycenter of Neptune-Triton and other external effects. We have compared our observations of

Table 4. Mean residuals μ and standard deviations to the mean σ of other CCD observations of Nereid

Set	year	N	μ ($\Delta\alpha\cos\delta$)	μ ($\Delta\delta$)	σ ($\Delta\alpha\cos\delta$)	σ ($\Delta\delta$)	Observatory
1	1993-1998	230	0.027	-0.130	0.184	0.150	874 - Itajuba (Laboratorio Nacional de Astrofisica)
2	2001	3	-0.070	0.333	0.153	0.008	568 - Mauna Kea
3	2002	3	-0.286	0.077	0.133	0.160	807 - Cerro Tololo Observatory, La Serena
4	2002	11	-0.131	0.178	0.125	0.101	644 - Palomar Mountain/NEAT
5	2003	1	-0.389	0.283			568 - Mauna Kea
6	2004	7	0.533	0.082	0.588	0.392	415 - Kambah, near Canberra
7	2006	18	-0.036	0.182	0.210	0.193	415 - Kambah, near Canberra
8	2006	3	0.060	0.615	0.117	0.247	213 - Observatorio Montcabre
9	2006	72	0.037	0.027	0.344	0.282	415 - Kambah, near Canberra
10	2006	1	0.057	-0.705			D35 - Lulin Observatory
11	2007	11	-0.271	0.067	0.290	0.350	415 - Kambah, near Canberra
12	2007	45	0.056	-0.156	0.270	0.321	415 - Kambah, near Canberra

Nereid to ephemeris of this satellite available on the IMCCE web site and derived from the theory of Jacobson (1991). For the planet Neptune, we have used the DE405 planetary ephemeris (Standish, 1998). In Table 3, we present the values of mean residuals μ and standard deviations to the mean σ of the absolute positions of Nereid for each of the four successive sets of observations defined above in Section 2.1. N is the number of observed positions for each set of observations.

As we can see in Table 3, the values of standard deviations σ of our observations are about 0.2 arcsec in right ascension as well as in declination. This value can be considered rather satisfactory as Nereid is a very faint satellite difficult to observe. Surprisingly, the 100a set, made with the smallest telescope that we used all along this observational campaign, appears to be the most accurate, with $\sigma \simeq 0.16$" in right ascension and $\sigma \simeq 0.13$" in declination, possibly due to the quite good weather conditions.

The high accuracy of our observations has been achieved certainly as we have used large CCD chips and the high accurate star catalogue UCAC2. Figure 2 displays the observed minus calculated residuals as a function of time for our observations. We can see that the absolute value of most residuals is lower than 0.3 arcsec. Also, no **significant** systematic positive or negative bias is observed on Fig. 2, accordingly to Table 3 presenting mean residuals always under 0.04", excepted in right ascension for the sets 100b and 216b. The first of these sets presents a slightly positive systematic mean residual ($\mu \simeq 0.08$") when the second set presents a hardly higher negative residual ($\mu \simeq$ -0.11"). However, these mean residuals remain very low and show that the accuracy of the Nereid Jacobson's ephemeris appears to be about 0.1 arcsec.

3.2 Comparison of our observations with other recent CCD observations of Nereid

The internet web site of the IMCCE provides some recent CCD Nereid observations ranging from 1993 to 2007 and made in different observatories as Itajuba, Mauna Kea, Cerro Tololo, Kambah, Montcabre, Palomar and Lulin. All these observations were not published, excepted those made in Itajuba (Veiga et al., 1999). They only had been collected by the Minor Planet Center which communicated them to the IMCCE. They represent a total of 175 observed positions, spreading over the period from 2001 to 2007. We have analysed all these observed data that we have compared to the theory to obtain positional residuals by using exactly the same procedure we used above for our own observations. Then, it has been possible to compare the accuracy of all these recent CCD observations to ours.

In Table 4, we have listed the mean residuals μ and the standard deviations to the mean σ for each set of these recent CCD observations, as we did in Table 3 for our observations.

So, the residuals of Nereid presented in Tables 3 and 4 involve all the available recent observations of this satellite from 1993 to 2007, all obtained with the CCD **techniques**. These residual statistics can appear as a complement for the recent observations of Nereid to those previouly given by Jacobson (1991) for all the earlier observations of this satellite, made from 1949 to 1989.

Now, we can compare the standard deviations to the mean σ given in Table 3 for our observations to those given in Table 4 for the other recent CCD observations. We can see that our observations, with σ values of about 0.2 arcsec, are more accurate than many other recent CCD observations which can present σ values between 0.3 and 0.6 arcsec, as those made in Kambah from 2004 to 2007. However, some other observations can present equal or slightly better standard deviations than ours, as those made in 2002 with the NEAT/Palomar instrument which is equipped with a CCD camera presenting a wider chip than ours. Also, the observations made in Itajuba with 3 different chips, appear to be very accurate, with σ values very close to those obtained for our 100a set of observations.

Now, the analysis of the mean residuals μ given in Table 4 for each set of observations shows that they generally are correlated with the values of the corresponding standard deviations σ. Consequently, as the most accurate sets of observations give rather low mean residuals, generaly hardly higher than 0.1 arcsec, we can confirm what we had shown above from the analysis of our own observations, that the accuracy of the used ephemeris of Nereid by Jacobson is about 0.1 arcsec.

4 CONCLUSION

In this paper, we have presented the 112 new CCD astrometric observed positions of Nereid that we have made in 2006 and 2007 at the Xinglong Station of Beijing observatory. Our observed positions present a rather high accuracy, with values of standard deviations to the mean of about 0.2 arcsec. This result should be due to the use of two large telescopes of 1m and 2.16m, equipped with large size CCD chips of 1340×1300 and 2048×2048 pixels. Also, the use of the high-density and high-accuracy star catalogue UCAC2 (Zacharias, 2004) in our astrometric reduction can have brought a supplement of quality in the resulting positions. Moreover, an analysis of other recent CCD observations of Nereid, available on the IMCCE web site, has shown that the accuracy of our observations is equal or better **than most of them,** even those which were made in the same years than ours (2006 and 2007).

So, we expect that the data presented in this paper will be of significant value for any future improvement of the knowledge of Nereid, and especially for our own research on this satellite, for which we plan to determine **in a new study of** the orbital parameters.

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